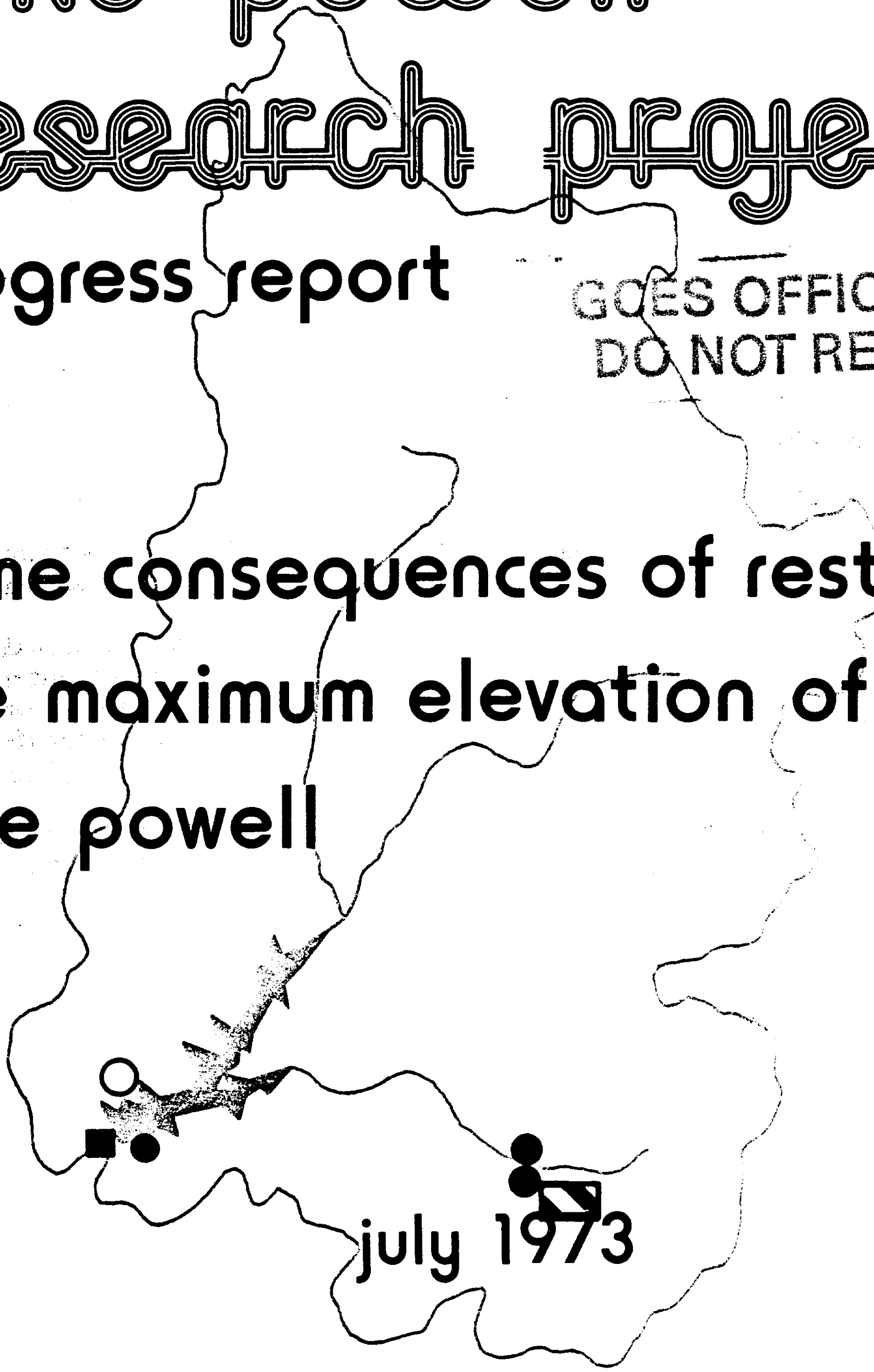
lake powell research project

progress report

some consequences of restricting the maximum elevation of lake powell



july 1973

National Science Foundation

Research Applied to National Needs

SOME CONSEQUENCES OF RESTRICTING THE MAXIMUM ELEVATION OF LAKE POWELL

a progress report written on behalf of the
LAKE POWELL RESEARCH PROJECT

by

ORSON L. ANDERSON
Natural Sciences Coordinator

and

PRISCILLA C. PERKINS
Executive Secretary

incorporating contributions by
S. Ben-David, F. L. Brown, C. L. Drake, D. E. Kidd,
G. C. Jacoby, Jr., N. M. Johnson, D. E. Mann, L. D. Potter,
R. C. Reynolds, Jr., R. H. Twiss, E. G. Walther, G. D. Weatherford
with special assistance from
S. Ben-David and G. D. Weatherford

Institute of Geophysics and Planetary Physics
University of California, Los Angeles 90024

July 1973

National Science Foundation
Research Applied to National Needs

TABLE OF CONTENTS

FIGURES

CREDITS

Ben-David assisted Anderson in the organization of this report. Weatherford assisted Anderson in the construction of Section II. Perkins edited the manuscript.

The following persons submitted drafts which were edited and incorporated into the report in the following sections: Section IA, Anderson and Perkins; IB, Anderson, Perkins and Weatherford; IC, Perkins and Anderson; IIA, Anderson and Weatherford; IIB, Jacoby, Anderson and Perkins; IIC, Weatherford and Anderson; IID, Anderson, Jacoby and Weatherford; IIIA1, Anderson and Jacoby; IIIA2, Jacoby; IIIA3, Anderson and Jacoby; IIIB1, Reynolds and Kidd; IIIB2, Kidd; IIIB3, Johnson; IIIC1, Potter and Drake; IIIC2, Anderson, Drake, Perkins, Potter, Walther, and Twiss; IIIC3, Walther; IIID1, Reynolds; IIID2, Anderson and Drake; IIID3, Anderson and Perkins; IIIE1, Ben-David and Brown; IIIE2, Ben-David, Brown and Drake; IIIE3, Ben-David and Anderson; IIIF1, Kidd, Potter, Reynolds and Anderson; IIIF2, Ben-David and Anderson; IIIF3, Anderson and Jacoby; IIIG, Weatherford and Mann.

The institutions and affiliations of the senior investigators are listed in Appendix 2. Subproject missions are listed in Appendix 3.

The manuscript was typed by Perkins. Jean Sells drafted Figures 1, 2, 4 and 7.

SOME CONSEQUENCES OF RESTRICTING THE MAXIMUM ELEVATION OF LAKE POWELL

I. INTRODUCTION

A. Action Variables

The Upper Colorado River Basin and the Lake Powell region are presently the foci of the converging demands of population growth, increased tourism, development of energy and water resources, and construction of coal-fired powerplants. These demands operate in a context of projected degradation of air and water quality and wilderness values.

The central feature of water management in the Upper Basin is Lake Powell, a multiple-use reservoir which began filling in 1963 behind Glen Canyon Dam on the Colorado River. The Lake Powell Research Project, funded by the Research Applied to National Needs division of the National Science Foundation, is monitoring the consequences of the creation of the lake and attendant developments. The Project is an interdisciplinary study group involving coordinated research in a variety of natural and social sciences.

Coordination between these diverse disciplines is accomplished by methods of systems analysis, whereby selected action variables are considered in common by each individual discipline within the Project. It is the goal of the Project to develop an empirical simulation model for the Lake Powell region, such that all disciplines will contribute toward operation of the model by consideration of the selected real problems which are the action variables.

For the past 6 months, the Project has been considering, as one action variable, the consequences of holding the level of Lake Powell at some arbitrary fixed maximum level. The Project is therefore able in this case to respond to requests for information about the environmental consequences of fixing lake level. Public attention concerning this action variable centers on the controversy over lake water entering the Rainbow Bridge National Monument (whenever the lake level exceeds 3606 feet in elevation). Although the Project has not been concerned directly with investigation of Rainbow Bridge itself, research by the Project should be of interest to groups which desire information about the environmental context of the National Monument and Lake Powell.

B. Scope of the Report

Five of the subsections of this report (in Section III) correspond to subsystems of the Project's systems analysis model: Water Budget, Lake System, Quality of Life, Legal and Political Factors, and Economic Impact. One special section treats geologic hazards which pertain to this particular action variable. Another section briefly describes some anticipated impacts outside the Lake Powell region, which are beyond the present mission of the Project.

To have covered all aspects of the expected consequences in the region resulting from the single action variable of lake level would have resulted in a much lengthier report than the present one. This report emphasizes only the more obvious impacts. Some impacts could not be investigated in detail because of the short time allowed for the preparation of the report. For example, it is difficult to determine how the impact of a maximum lake elevation of 3606 feet would affect the Navajo Nation, without first determining the extent of Navajo expectations for recreational investments along the lake shore. To undertake the necessary research for this problem would involve a considerable diversion of money and time in the midst of the Project's summer field season.

Some impacts were not pursued because the primary purpose of the Project's system analysis effort is to develop the capability of examining the consequences of a wide variety of action variables rather than pursuing all the ramifications of any one action variable. As a result, some of the observations of this report may seem superficial to special-interest groups. If the Project were to pursue diligently each impact to its logical conclusion, the Project would become more like an investigation agency than a research consortium. The Project is determined to maintain course and not be diverted towards a detailed examination of many special consequences. A number of impacts were not considered by this study group since they were thought to be outside the focus of the Project. For example, the impact on revenues resulting from possible changes in hydroelectric power sales was not investigated.

The Project has always maintained that its members should not be investigating problems in the Lake Powell region which appear to be adequately pursued by researchers of other groups or agencies. It is not the mission of the Project to compete with Federal agencies doing research in the area, such as the Bureau of Reclamation, the National Park Service, or the U. S. Geological Survey. For that reason, this report uses considerable basic data collected by the Bureau of Reclamation and the U. S. Geological Survey. To the extent, if any, that such basic data is inadequate or erroneous, the dependent analysis contained herein will be accordingly subject to correction.

Some aspects of the analysis contained in this report are dependent in large part on basic hydrologic data provided by the Bureau of Reclamation and the U. S. Geological Survey. The Bureau of Reclamation is currently involved in litigation with Friends of the Earth involving Rainbow Bridge (Friends of Earth vs. Ellis Armstrong, pending). The Project is aware of the problem that analysis based on Bureau of Reclamation data may appear to favor the Bureau's position in this litigation. Information from independently funded hydrologic modeling of the Colorado Basin would be needed to confirm some of the Bureau's conclusions. Under these circumstances, it is unfortunate that additional independent sources of data are not presently available. This situation illustrates a need for independent, interdisciplinary environmental assessment free from the external legal and political constraints which arise from time to time.

There is no intention or desire on the part of the Lake Powell Research Project to further the interests of any one party in the pending litigation.

The conclusions of this report should be considered temporary and subject to change. It is a progress report, and will probably become the basis for a more scholarly report, after field investigations are completed.

C. Conflict in Aesthetic and Economic Expectations

Glen Canyon National Recreation Area and Rainbow Bridge National Monument share a common boundary, but the two areas were set aside at different times for different purposes. The National Monument was proclaimed in 1910 to preserve an isolated, unique, scenic feature in desert wilderness. The National Recreation Area, including Glen Canyon Dam and Lake Powell, was established in 1963 to provide spectacular public facilities for popular boating, fishing, water-skiing, and back-country jeep trips.

Much of the controversy and conflict of interest pertaining to the areas can be traced to the geographic juxtaposition of reserves dedicated to public use under two different ethics: one, that of preservation in perpetuity of a unique feature of the American wilderness, and the other, the management of water resources for economic development and recreational use. The conflict between the preservation and the developmental-recreational ethics is revealed in some of the facets of this report.

The Upper Colorado River Basin is a region that is simultaneously wealthy in mineral resources but poor in water resources. The prospect of extensive exploitation of these mineral resources becomes more imminent as national energy demands increase. Therefore, the prospect of large-scale regional energy production is superimposed upon the historic problem of equitable water allocation among many claimants. The development of Upper Basin energy resources will make additional large demands on an already over-allocated water system. Large regional water development projects in the Upper Basin, postponed for decades, are just nearing final authorization and completion at a time when the overall water quality being delivered downstream has reached critical salinity levels.

Much of the conflict between the various groups with conflicting economic expectations is inherent in the phrase, "multiple-use reservoir." The conflicts among groups responsible for preservation of water and environmental quality, the prevention of a regional energy crisis, the growth of the regional economy, and the establishment of new agricultural complexes is implied in some aspects of this report, but it is not the intention of the report to make judgments as to which of these interest groups is to be favored in lake-level management. The Lake Powell Research Project does not wish to make a judgment as to what extent economic expectations should be denied in order to satisfy aesthetic expectations. The primary purpose of the studies of the Project is to reveal the consequences of certain water management alternatives (in this case the consequences of holding the lake level fixed) in the context of the various regional and national expectations.

II. SETTING FOR THE RAINBOW BRIDGE CONTROVERSY

A. Rainbow Bridge National Monument and Lake Powell

Congress authorized the Colorado River Storage Project Act on April 11, 1956. The juxtaposition of two provisions in the Act has led to a court battle over the entry of Lake Powell into the National Monument. Section 1 of the Act provides "that as part of the Glen Canyon Unit the Secretary of Interior shall take adequate protective measures to preclude impairment of the Rainbow Bridge National Monument." Section 3 provides in part: "It is the intention of Congress that no dam or reservoir constructed under the authorization of this Act shall be within any national park or monument." Congress has subsequently prohibited the expenditure of any funds by the Secretary of Interior to protect the National Monument by protective features such as coffer dams.

The Friends of the Earth, the Wasatch Mountain Club, and Kenneth G. Sleight filed a complaint in the United States District Court for the District of Columbia on November 5, 1970 against the Commissioner of the Bureau of Reclamation and the Secretary of the Interior. The case was transferred to the District Court for District of Utah in 1971 at the request of the government. The complaint asked that the Commissioner and the Secretary of the Interior be required to: "(a) prevent Glen Canyon Reservoir (commonly known as Lake Powell) from invading the boundaries of Rainbow Bridge National Monument, and (b) take adequate protective measures to preclude impairment of Rainbow Bridge National Monument pursuant to their duties under Sections 1 and 3 of the Colorado River Storage Project Act, Act of April 11, 1956."

Waters of Lake Powell at elevation 3606 entered Rainbow Bridge National Monument in the canyon of Bridge Creek on or about May 15, 1971, and remained within the monument until September 1971 when the lake level dropped. Lake Powell again entered the Monument on October 20, 1972, and retreated on January 1, 1973. On February 28, 1973, Judge Willis W. Ritter of the District Court for Utah issued an Order, Judgment and Decree prohibiting storage water of Lake Powell from entering the boundaries of the Rainbow Bridge National Monument. Subsequently on March 13, 1973, the Department of Justice filed an appeal and a motion for stay (i.e. suspension of the order) pending the outcome of the appeal before the Tenth Circuit Court of Appeals.

The Tenth Circuit approved the stay in May, 1973, but at this writing has not rendered a final decision on the appeal. By approving the stay, the Tenth Circuit allowed the Bureau of Reclamation to operate the reservoir under the conditions which prevailed before Judge Ritter issued his order. The lake reentered the monument on May 22, 1973. At the time of the preparation of this report (July 1, 1973) the waters of Lake Powell are within the

National Monument at an elevation of 3637 feet and are rising. It is entirely possible that the lake may approach elevation 3650 during 1973, before it recedes after the spring runoff is completed. Figure 1 shows the topography of Bridge Creek and the location of Rainbow Bridge with respect to areas covered by Lake Powell at elevations 3606, 3650, and 3700.

If the Tenth Circuit affirms Judge Ritter's judgment prohibiting the waters from entering the Monument, the waters would be withdrawn again, unless the case were to be reviewed by the Supreme Court of the United States which could grant stay pending its final decision. Even though it is still unclear whether the waters of Lake Powell can lawfully remain in the Monument, much of the environmental impact is determined by the fact that the lake is present in the Monument today and will stay within the Monument for at least the immediate future.

In assessing impact therefore, one should not only consider what might happen if the maximum lake level is restricted to elevation 3606. The prospects are that the lake level will fluctuate for some time in the future above and below elevation 3606. Important impacts to be considered are the consequences of large fluctuations in lake level caused by periodic drawdowns and variations in the natural runoff.

B. Storage Capacity Parameters

The storage capacity of Lake Powell is a large fraction of the total capacity of all regulated reservoirs in the Upper Colorado River Basin. The plans for the development of the Colorado River Storage Project (CRSP) in the Upper Basin always considered Lake Powell to be the main impoundment for river and power management. The other main regulated reservoirs in the Upper Basin are Fontenelle, Flaming Gorge, Curecanti (Blue Mesa and Morrow Point units), and Navajo, with a combined active storage capacity of 6.7 million acre-feet (maf). Lake Powell at elevation 3700 has an active capacity of 25 maf, so the total maximum active capacity of the Upper Basin system is 31.7 maf. The volume of Lake Powell at elevation 3606 is 12.7 maf (Figure 2) or 12.3 maf less than its designed maximum capacity. If lake level is restricted to elevation 3606, the total Upper Basin regulated system capacity becomes 19 maf. This represents a 39% reduction in the designed maximum active storage capacity of the whole system of regulated reservoirs. (Capacity figures used in the above discussion and calculation were obtained from the Bureau of Reclamation Annual Report, "1972 Operation of the Colorado River Basin: 1973 Projected Operations", January, 1973.)

The active storage capacity of Lake Powell at various elevations is controlled by the geometry of the canyons filled by the reservoir. The deepest parts of the canyons are very narrow, but the upper parts are much wider. Therefore, the amount of water which can be stored in the reservoir increases most rapidly with increases of lake level at the highest possible elevations.

Figure 1

TOPOGRAPHY NEAR RAINBOW BRIDGE

Areas covered by waters of Lake Powell at three different lake elevations (3606, 3650, and 3700 feet above sea level) with respect to the location of Rainbow Bridge.

Source: Contours traced from unpublished topographic maps of the Bureau of Reclamation

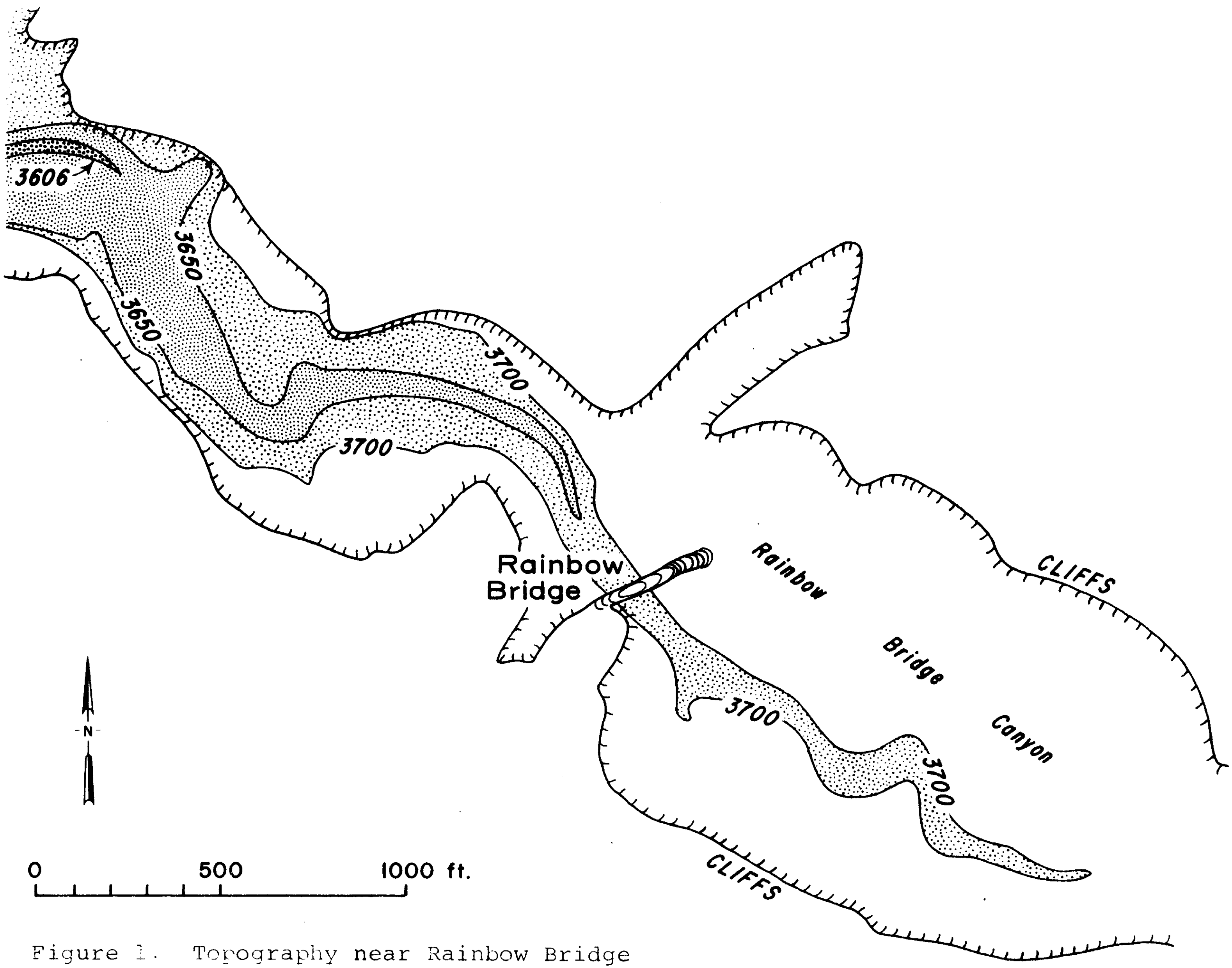


Figure 1. Topography near Rainbow Bridge

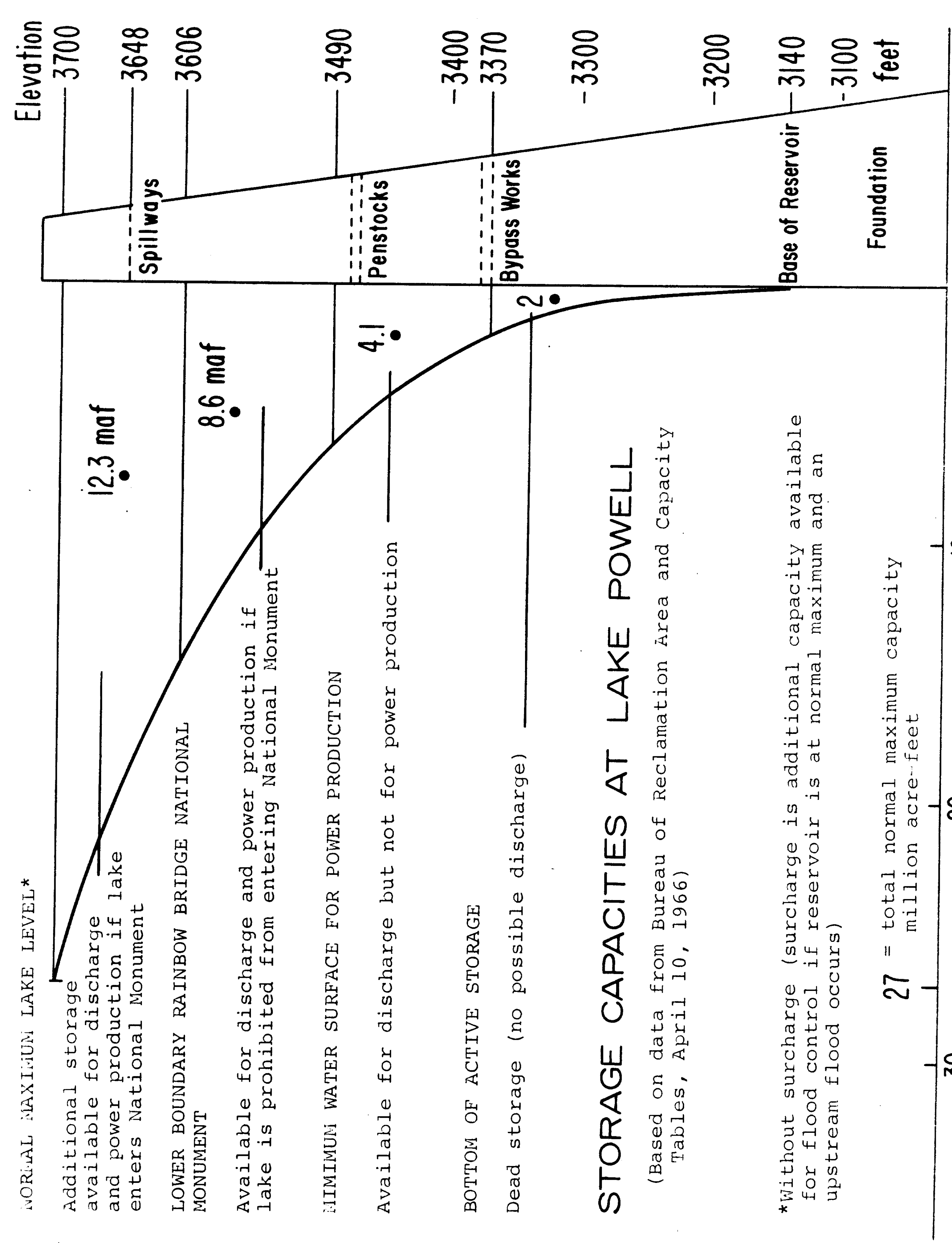
Figure 2

STORAGE CAPACITIES AT LAKE POWELL

Storage capacity available at various elevations of Lake Powell

Source: Based on Bureau of Reclamation Area and Capacity Tables, April 10, 1966

Figure 2: Storage Capacities at Lake Powell



The design of Glen Canyon Dam places certain limitations on efficient operating levels of the reservoir. The dam is designed for a normal maximum water surface elevation of 3700 feet above sea level, without surcharge. The spillway crests are at elevation 3648; the turbine inlets are at elevation 3470 feet, but operationally the turbine intake must be at least at elevation 3490 to prevent the admission of damaging air. The lower boundary of Rainbow Bridge National Monument is at elevation 3606 on Bridge Creek. These geometrical constraints on reservoir operation are shown in Figure 2.

The operating criteria for the dam and lake require certain minimal limits of power production and discharges downstream to satisfy water allocations for the Lower Colorado River Basin and Mexico. One of the main purposes of Lake Powell is to provide a large storage capacity so that water can be stored during wet years and carried over for availability in dry years ("carry-over storage").

Figure 2 shows the water surface elevation limits for power production. If the lake level is fixed at or below the lower boundary of Rainbow Bridge National Monument (elevation 3606), up to 14.7 maf of water can be stored in the reservoir. However, only 8.6 maf of this water is usable for power production. Water storage which can be used for power production is called active power-generating storage. On the other hand, if the lake is allowed to reach its full capacity, the reservoir can contain 27 maf of water, of which 20.9 maf is usable for power production.

C. <u>Water Management Constraints and Guidelines</u>

The policy matrix within which lake level decisions are made includes the following legal mechanisms:

1) Interstate Compacts

   a. 1922 Colorado River Compact

   b. 1948 Upper Colorado River Basin Compact

2) International Treaties

   a. Mexican Water Treaty of 1944 and subsequent Minute Orders

3) Acts of Congress

   a. Boulder Canyon Project Act of 1928

   b. Boulder Canyon Project Adjustment Act of 1940 as amended

c. Colorado River Storage Project Act of 1956 as amended

d. Colorado River Basin Project Act of 1968

e. National Environmental Policy Act of 1969

4) Administrative Regulations

a. Glen Canyon Filling Criteria of 1962

b. Criteria for Coordinated Long-Range Operation of Colorado River Reservoirs Pursuant to the Colorado River Basin Project Act of September 30, 1968, published in the Federal Register on June 9, 1970

5) Judicial Decisions

a. Arizona v. California (1963)

b. Friends of Earth vs. Ellis Armstrong, pending

6) Contracts

a. Water delivery

b. Sale of hydroelectric power

c. Concessionaire agreements

Unless restricted by court order or otherwise, the Glen Canyon Dam and Powerplant function to meet a number of legal obligations and policy objectives. First, the 25 maf active storage capacity of the dam is available to assist the Upper Basin in meeting its obligation under the 1922 Compact to deliver 75 maf to the Lower Basin at the Lee Ferry accounting point during each 10-consecutive-year period. (The Compact does not provide for a minimum annual release.) Second, although the full extent of the obligation of the Upper Basin states to contribute toward the 1.5 maf per annum delivered to Mexico under the 1944 Mexican Water Treaty is a matter of dispute, it is clear that the storage capacity of Glen Canyon Dam assists the Upper Basin in fulfilling any delivery requirement ultimately imposed upon it. As a matter of current practice, for example, 8.2 maf (which approximates the sum of 7.5 maf plus one-half of the 1.5 maf Mexican obligation) is regarded as the minimum amount to be delivered annually at Lee Ferry. Third, Lake Powell provides a sizeable power pool (900,000 kilowatts). Glen Canyon Dam is regarded as the principal "cash register" of the Colorado River Storage Project; it produces most of the revenue for the Upper Colorado River Basin Fund on which project repayment and subsidy depend.

The Colorado River Basin Project Act of 1968 required the Secretary of Interior to adopt criteria for long range operation under guidelines of the Act, which he did in 1970. Those 1970 criteria incorporate the major legal constraints and seek to strike a balance between Upper and Lower Basin interests. They assume the availability of the full designed storage capacity of Glen Canyon Dam and reservoir.

The 1970 Criteria provide that sufficient water is to be retained in storage in the Upper Basin reservoirs to help make up any deficiencies in the Mexican Treaty obligation and to assure delivery of water at Lee Ferry as required by the Colorado River Compact, without impairment of Upper Basin consumptive uses. This storage, in amounts to be determined by forecasts, has first call on the quantity of flow above the dam. If, in any given water year, the "active storage forecast" for Upper Basin reservoirs is less than the amount of storage determined to be needed, or, if the active storage forecast for Lake Powell is less than that for Lake Mead, then water in excess of this storage requirement may be released for domestic and agricultural uses in the Lower Basin, provided that the active storage in Lake Powell is at least equal to that in Lake Mead. The objective shall be to maintain a minimum release of water from Lake Powell of 8.2 maf for that year.

The hydrologic question posed by setting the lake level at elevation 3606 is whether the 8.6 maf of active power-qenerating storage is likely to be sufficient over time to allow delivery downstream for compliance with regional water allocations. Under the present institutional framework, unless sufficient storage capacity is provided at Lake Powell to satisfy these needs, there is reportedly a likelihood that Upper Basin reservoirs would have to be drawn down lower in dry years than would otherwise be the case, thereby denying consumptive uses in the Upper Basin.

An examination of the flow records at Lee Ferry for the past 75 years (Figure 3) reveals that there have been several periods since the signing of the 1922 Colorado River Compact for which an 8.6 maf active capacity at Lake Powell, when combined with the other active storage capacity in the Upper Basin, would not have been adequate to satisfy present legal requirements for power production and water allocation in the Upper and Lower Colorado River Basins. For example, the decade 1931-1940 was so dry that an 8.6 maf active storage would not have sufficed.

D. The Elevation 3606 Limit for Lake Powell

The Bureau of Reclamation states that it would be impossible in the long term to operate the dam under the 3606 limit and still satisfy the criteria of the Colorado River Basin Project Act of 1968 (see Affidavit, Appendix 1). If so, one alternative would be to seek new legal arrangements in place of the present legal and

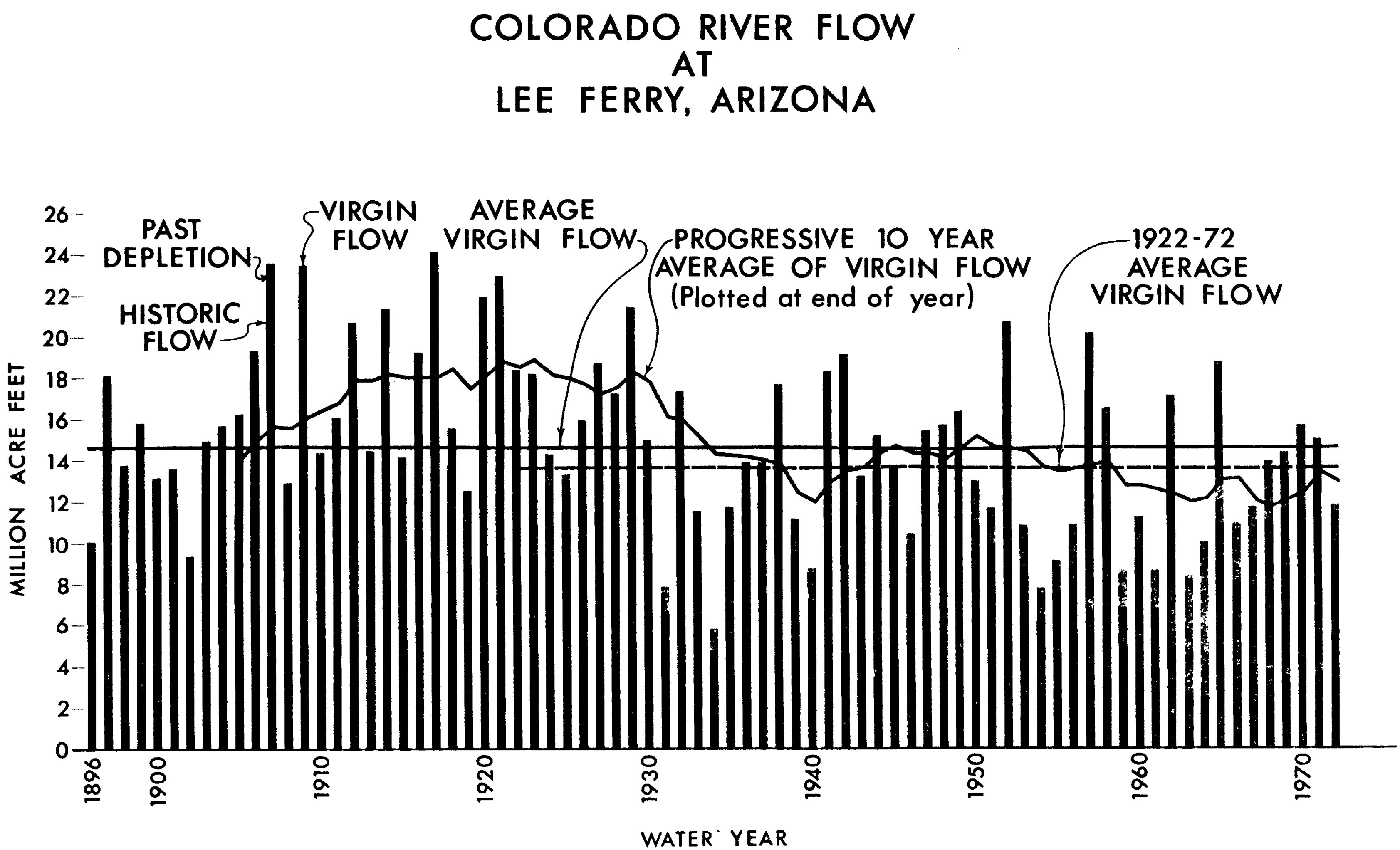


Figure 3: Runoff at Lee Ferry

Source: Bureau of Reclamation

institutional constraints (Section III G). It would appear, however, that the priorities of the current criteria for operating the Upper Basin reservoirs are such that in case of insufficient water flow to satisfy both Upper and Lower Basin allotments, shortages would be assumed by the Upper Basin (Affidavit, Appendix 1).

The position of the Bureau of Reclamation is, that if the court ruling is allowed to stand, the Upper Basin states of Utah, Colorado, Wyoming and New Mexico will lose an annual average total of 1 maf of water which they otherwise could receive for consumptive use under the Colorado River Compact. The Bureau argues that without the storage available if Lake Powell is filled to elevation 3700, there will not be sufficient storage capacity to ensure releases to satisfy the Lower Basin in years of water shortages, and at the same time have the anticipated 5.6 maf annual beneficial consumptive use in the Upper Basin (Affidavit, Appendix 1). The Lake Powell Research Project has not yet verified this assertion about the 1 maf loss to the Upper Basin by detailed hydrologic analysis using computer models. Rough calculations, based upon the flow records (Figure 3), indicate this assertion is probably reasonable, and for purposes of this report, it will not be challenged.

Unless a federally funded coffer dam is constructed to prevent Lake Powell from entering the National Monument, the Rainbow Bridge litigation reduces the choice of maximum lake level to two alternatives: elevation 3606 or 3700. Each alternative reflects a complex of values.

Elevation 3606 is the boundary of a National Monument. It therefore has potent symbolic value, as demonstrated both by the history of the Echo Park controversy in the 1950's, involving a proposed reservoir in Dinosaur National Monument, and by the resultant prohibition in Section 3 of the 1956 Colorado River Storage Project Act (Section II A, this report). Environmental interest groups have drawn the battle line at the monument boundary. Any relaxation of this perimeter, in their view, would create a precedent under which other National Monuments could be violated. The alternatives of elevation 3606 without a coffer dam or 3700 with such a dam are thereby presented. The present issue is not whether lake water should or should not be allowed directly under Rainbow Bridge itself, but whether lake water should be allowed to enter the boundaries of the Monument downstream from Rainbow Bridge.

Elevation 3700 represents the constructed capacity of facilities dedicated to meeting a panoply of economic expectations. The Bureau of Reclamation, whose mission it is to establish and maintain operable reclamation projects within certain management constraints and guidelines, wishes to utilize the full capacity and flexibility of the Glen Canyon complex to fulfill its mission.

Yet Congress has prohibited the expenditure of funds for a coffer dam, predisposing the Bureau to the alternative of elevation 3700 in the absence of the coffer dam.

The analysis contained herein does not deal with intermediate alternatives which might be considered in the future. For example, one such alternative would be to set the maximum limit of lake level at elevation 3648, the elevation of the spillway crests. If lake level were set at elevation 3648, it would be possible to contain the lake within that level by spillway releases when the runoff rate into the lake is high. This alternative would reduce the deleterious effects accompanying large fluctuations in lake level caused by major winter drawdowns necessary if the maximum lake level is set at elevation 3606 (Section III A 1). Consideration of such alternative levels between 3606 and 3700 may be pursued as an action variable in the future by the Project.

It should be made clear that the Lake Powell Research Project, cognizant of underlying policy issues involved in the Rainbow Bridge controversy, is not advocating in this report any "physical solution" for settlement of that dispute.

III. IMPACTS FROM VARIOUS MAXIMUM LAKE LEVELS

A. Water Budget

1. Discharge Capacity of the Dam

If the lake level maximum is set at elevation 3606, it may be seen from Figure 2 that it becomes important to hold the lake level as close as possible to the 3606 level in order to have at least 8.6 maf active storage needed to maximize electric power generation and reserve water storage. If for any reason the lake level must be lowered in anticipation of high spring runoff, then the lake must be filled immediately to the 3606 level after the runoff in order to maximize operating conditions. It becomes important to the operation of the whole system whether or not the dam has enough discharge capacity to pass large spring runoffs and maintain the level near 3606 without exceeding that limit.

The spillway crests of the dam are at elevation 3648, so that all water below that level must pass through the turbines and/or the outlet bypass at a limited discharge rate. At lake elevations less than 3648, the maximum possible discharge rate through the turbines and the outlet bypass at elevation 3370 is 43,000 cubic feet per second (cfs) on a sustained basis. However, there are many years in which the spring-runoff rate exceeds 50,000 cfs into the lake. This high rate was observed for spring runoff in 1973.

If the maximum lake level is restricted to elevation 3606, it becomes necessary to lower the lake in the winter in anticipation of a possibly heavy spring runoff. A projection of runoff cannot be made until January when snowpack information becomes available. This maneuver would be necessary to prevent the lake from entering Rainbow Bridge National Monument, but would severely restrict the capability of the dam to impound water in years of high runoff for subsequent use in dry years.

Even with winter drawdowns to elevation 3490 (the turbine intakes), the National Monument might be invaded by lake water in a rare Colorado flood year such as occurred in 1884. It has been suggested that the spillways of the dam be modified to allow faster water release from levels substantially below the spillway crests at elevation 3648. Such a modification would enable the 3606 maximum to be maintained. Should the new spillway facilities be constructed, it would no longer be necessary to lower the lake as drastically in the winter below elevation 3606. Occasional large spring runoffs could then be passed downstream without inundation of the National Monument. However, even the construction of spillways would not lessen the prospective loss of water allotment for the Upper Basin states. Further, after several years of protracted drought, the water allotment demand and the power demand could exceed the 8.6-maf active power-generating storage capacity.

It is important to emphasize that if the lake level is to be held at a maximum elevation of 3606, and the present maximum sustained discharge rate of 43,000 cfs is not increased, there will be large fluctuations of the lake level caused by irregular seasonal flow in the upstream tributaries. Such lake level fluctuations would have important impacts on the lake environment (Sections III B and C).

2. Evaporation

As a first approximation, evaporation losses may be considered to be directly proportional to surface area. At elevation 3606, the lake surface area is 101,770 acres; at elevation 3700, the surface area would be 161,390 acres. Present estimates of annual evaporation range from 4 to 6 feet per year. The range in estimated values is due to different techniques of measurement and the locations where the measurements are made.

The refinement of the evaporation value to a more reliable and well-defined figure is one of the important goals of the Lake Powell Research Project. Until this value is determined, the Project is using an intermediate value of 65 inches per year. Assuming this latter value, the evaporation loss would be 0.55 maf per year for lake elevation 3606 and 0.87 maf for elevation 3700 (Figure 4). These figures are "gross" evaporation and include the amount of water (0.225 maf) which would have evaporated each year from the river system even without the creation of Lake Powell. The Project concludes that raising the level of Lake Powell from elevation 3606 to 3700 would cause a net increase in evaporation of about 0.3 maf per year. The Project estimates that the increase in evaporation to be expected from operating the lake at elevation 3700 instead of 3606 would be 3 maf in the 10 years, or 6 maf for the next 20 years.

Figure 5 shows the amount of net evaporation (that due to the creation of the lake) for Lake Powell in the decade ending February 1973, according to the Bureau of Reclamation. The amount is 2.52 maf, which is 3.23% of the total flow past the dam in the same period (77.98 maf). The Project considers these to be reasonable figures.

3. Bank Storage

Figure 5 shows the amount of bank storage accumulated at Lake Powell since the dam was closed in 1963, according to the Bureau of Reclamation. The Lake Powell Research Project believes that this estimate is essentially correct, and the Project is attempting

Figure 4

EVAPORATION CURVES

Calculated annual evaporation as a function of lake elevation for three evaporation rates: 4, 5.417 and 6 feet per year

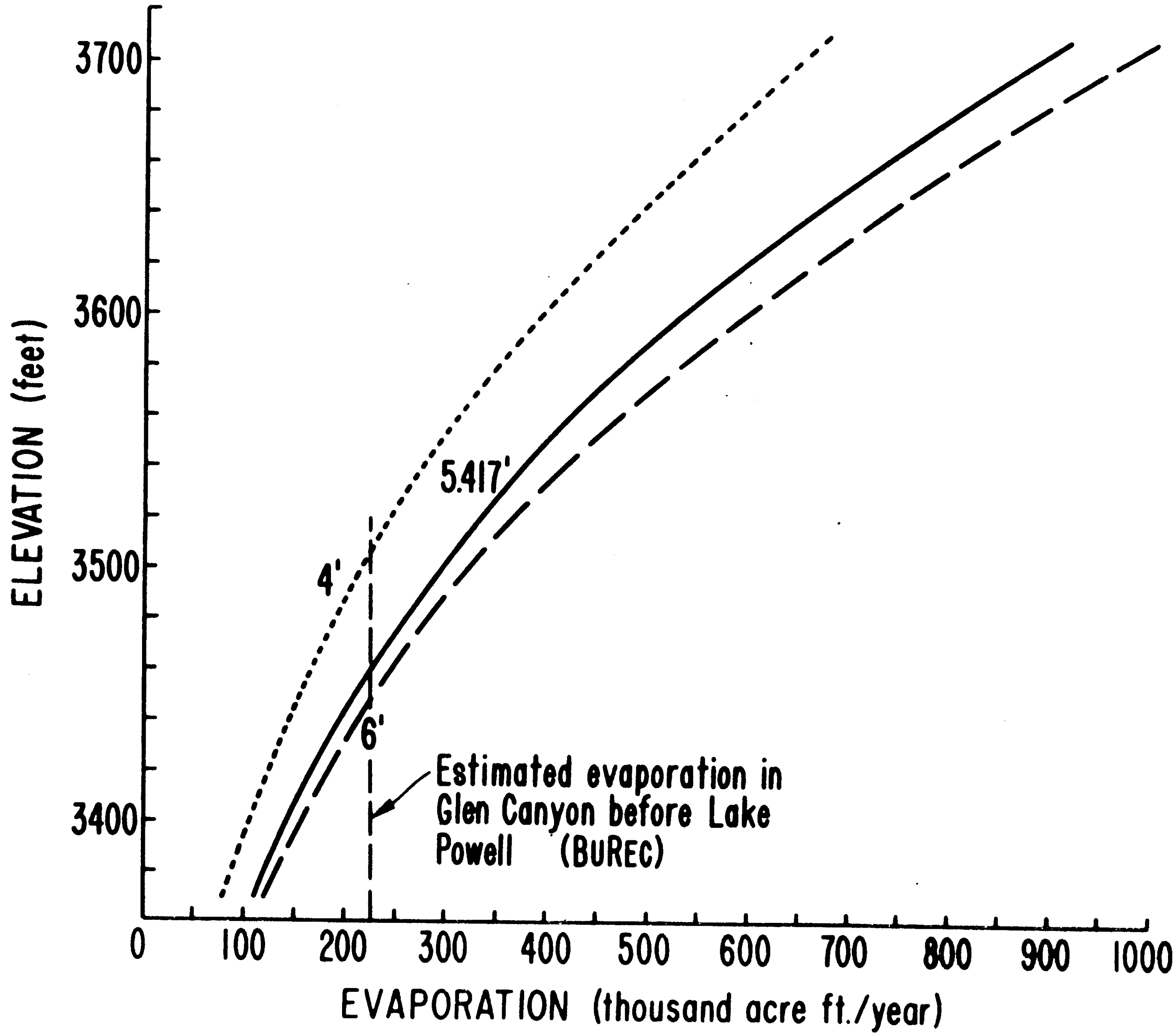


Figure 4: Evaporation Curves

HISTORIC DISPOSITION OF RUNOFF
ABOVE GLEN CANYON DAM
JAN. 1963 TO FEB. 1973
106,826,000 A.F.

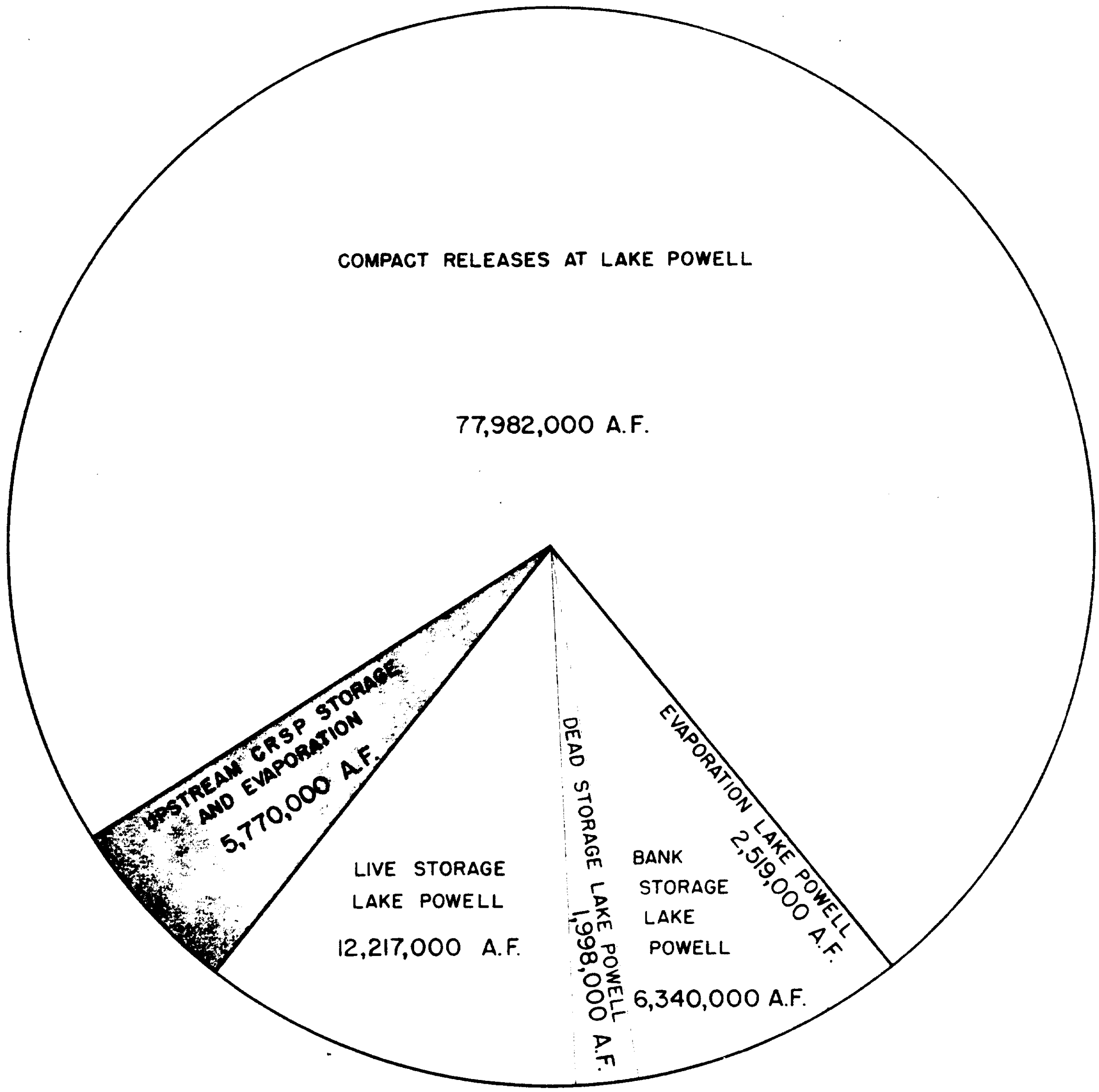


Figure 5: Evaporation and Bank Storage Losses

Source: Bureau of Reclamation

to improve the accuracy of the bank storage figure by field measurements in cooperation with the Bureau of Reclamation. The present estimates of accumulated bank storage by the Lake Powell Research Project are 6.5 to 7 maf as of the fall of 1972.

When lake surface elevation is held constant, the annual rate of accumulation of bank storage tends to diminish with time as the rocks surrounding the lake become saturated. The average rate over the past decade has been approximately 0.65 maf per year during the initial filling stages. If the reservoir is held at elevation 3606 and kept near that elevation, the eventual accumulated bank storage may increase to a total of 9 maf, assuming that the annual rate continues to decrease.

Bank storage is largely influenced by head or driving force which pushes water into the rock walls of the reservoir. The head at the dam would be 94 feet higher for operation of the lake at elevation 3700 rather than 3606. If the lake level were held at elevation 3700 for 2 or 3 years, the Project estimates that bank storage would reach about 8.5 maf.

The Project estimates that the eventual amount of bank storage might be 20% greater if the lake were operated at the maximum level than if it were restricted to elevation 3606. The accumulated bank storage in the next decade would be about 2 maf greater for operation at 3700 instead of 3606. If the lake level were held at 3700 for 10 years and 20 years, total bank storage might reach 12 and 15 maf respectively. However, it should be noted that holding the lake at normal maximum capacity for decades is very unlikely. In the 25 years prior to the initiation of storage at Lake Powell, Lake Mead averaged about 75% of capacity.

It should also be noted that permission to reach elevation 3700 does not automatically raise the lake to that level. After a series of high runoff years the lake may reach that level, but then it may be appreciably lowered during several drier years. During such a dry period there may be sizeable return flow of bank storage as the lake level drops. Therefore, the estimates of bank storage for the water surface elevation 3700 must be viewed as an extreme case.

B. The Lake System

1. Water Quality

If the lake level is raised to the maximum capacity instead of being held at elevation 3606, there will be an impact on the water quality. As the volume of the lake almost doubles, from 14.7 maf at elevation 3606 to 27.0 maf at 3700, the flow of the river water through the impoundment will be slowed due to the increased friction caused by greater depth. Incoming water from the Colorado

River collides with the slower moving lake water and sediment drops out of the incoming flow. As the lake volume increases, the deposition of sediment will occur farther upstream. A consequence of this process will be that clearer water will be present in the lake farther upstream in the impoundment than if the lake level were maintained at elevation 3606.

Raising the level of Lake Powell from elevation 3606 to 3700 will cause a significant increase in the percentage of shallow bays and estuaries in the lake. Where light penetration reaches more easily into the lake, in clearer water and in shallower areas, greater photosynthetic activity by algae may be anticipated. There will thus be considerably greater photosynthetic activity in the lake at the 3700 level.

Calcium carbonate precipitation is caused by pH changes resulting from photosynthetic activity of both floating and attached algae. Consequently, an increase in calcium carbonate precipitation is expected in the lake if it is operated at the maximum level. Present estimates indicate that total reduction of salinity in the water of Lake Powell, due to carbonate precipitation, averages approximately 5% for the lake at elevation 3606. The salinity reduction should increase to 7 or 8% if the level is raised to 3700, unless significant contributions to salinity from inundation of additional soil and bedrock are added by flooding of larger surface areas. A temporary increase in sulfate concentration may be expected due to the rise in lake level from leaching of newly inundated rocks and soils. However, the rate of the leaching process should diminish in a few years, so that the long-term effects of maximum lake level will be dominated by the diminished calcium carbonate salt load. A consequence of raising the water level to 3700 should therefore be improved water quality in the lake and reduced salinity in the lake due to the increased removal of calcium carbonate from the lake water.

2. The Biological Ecosystem

Operation of Lake Powell at elevation 3700 may be expected to promote greater photosynthetic activity by algae in the upper lake levels and higher carbon production in the fish food chain. Carbon production from photosynthesis in the lower 23 miles of the reservoir may double to about 140,000 metric tons annually. Greater production may also be anticipated in the northern part of the reservoir. As the waters inundate more land surface, they will leach out nutrients which will, in turn, stimulate algal growth, zooplankton growth, and fish production.

The classic view is that increasing water volume provides more space for living organisms. Algae increase in quantity to fill newly provided space. Since they provide food for zooplankton, it is most probable that the quantity of zooplankton will increase.

Fish feed on zooplankton and the quantity of fish will increase as the reservoir volume increases. Eventually a balance is reached between the quantities of phytoplankton, zooplankton, and fish. This balance is maintained for several years until the supply of nutrients becomes more limiting to algae. Depletion of nutrients occurs because they are being released in the deep water discharges from the impoundment. Since filling of the lake may take several years, the productive life of the reservoir will be maintained for a longer period of time. Reservoirs are most active in terms of fish production during their early years, but once the designed water elevation is reached, productivity decreases over the years and biological water quality usually also decreases. In brief, reservoir productivity as well as water quality will be improved if Lake Powell is operated at elevation 3700.

3. Lake Circulation

If lake level were raised to elevation 3700 there would be a number of impacts on the lake circulation, most conspicuous of which would be an increase in the heat budget of the lake due to the larger surface area. This process will tend to increase the intensity of convective mixing in the upper layers of the lake. Unlike most lakes, Lake Powell has a deep, narrow channel. Thus the extra heat will not necessarily extend the convective mixing to deeper water than at present. This is not too serious, however, in view of the fact that the bottom water is not presently oxygenated by convective mixing, but rather by advective transport. The volume and configuration of the main channel, which forms the bottom, will stay the same regardless of how deep the lake becomes. Also, the winter underflow current is restricted to this main channel. It is this underflow current which is the agent which oxygenates the bottom waters of the lake. Therefore, if the size of the channel and the size of the underflow current remain constant, the lake bottom should not become anerobic, even if the lake level is raised.

The Project concludes that at the 3600-foot level, the lake is "healthy," which means that it is well-mixed, well-oxygenated, and oligotrophic. Raising the lake level to the 3700 level should not be deleterious to the health of the lake, unless there are unforeseen changes in salinity, hydrology, or climate.

It has been proposed that new spillways for the dam be constructed at a lower elevation than the present crests at 3648. The circulation of the lake would be profoundly affected by a lower spillway elevation which has been proposed as a method to control high spring runoff if elevation 3606 is set as the lake level maximum. At the present time, the mixing (oxygenation) of the lower lake is contingent upon water withdrawals through the dam at mid-depth (elevations 3490 and 3370). A persistent withdrawal from the upper layers of the lake through a surface spillway would substantially alter the mode of circulation in the lake. The present mode of circulation is "healthy." It is conceivable that a large change in the circulation of the lake could degrade the present "healthy" circulation. At the present time, the circulation of the lake appears to be controlled by the principal withdrawals at the penstocks and bypass works.

Large fluctuations in lake level will result in accelerated slumping of talus slopes and fans of unconsolidated sediments along the shoreline (Section III D) during the drawdown periods. Material from these slumps will be transported into the main channel and will create underwater dams which ultimately affect the circulation pattern of the lake.

The Project expects that drawdowns of the lake will also affect the circulation by accelerating advection. A rising lake level retards advection. Therefore, if the lake level oscillates around some average level, the opposing effects on advection should cancel each other in time.

C. Quality of Life

The quality of the environment is a significant factor in the quality of life in the Lake Powell region for both residents and recreational visitors. The action variable of lake level operates on three aspects of the quality of life in the Lake Powell region which are being studied by the Project: (1) quality of developed recreation, especially along the shoreline of Lake Powell in Glen Canyon National Recreation Area, (2) quality of wilderness recreation and preservation, and (3) regional air quality.

Developed recreation is based on facilities such as motels, marinas, public campsites, and motorized pleasure vehicles for land and water transport. Wilderness recreation is based on quiet solitude and a minimum of equipment for backpacking or simple hiking in the absence of motorized vehicles.

1. Shoreline Recreation

In the Lake Powell region, recreation value depends greatly on the quality of the shoreline, and upon the availability of desirable campsites. Although there is always a shoreline, regardless of the water level, there are definite impacts of either different water levels or fluctuations of those levels on the shoreline ecology. There will be seasonal drawdowns no matter which maximum level is established.

The principal effects of a seasonal drawdown are: (1) textural changes involving a general trend toward coarser shoreline materials, e.g., removal of clay and silt from talus slopes and alluvium, leaving bouldery shores less suited for campsite use; (2) the exposure of about 20 vertical feet of drowned dead vegetation in various states of decomposition; (3) the exposure of a white band, or "bathtub ring," on cliff walls; and (4) invasion of the drawdown zone by exotic vegetation. The drawdown zone on sandy shoreline which is exposed from July to January is invaded in the fall by a dense stand of tamarisk seedlings which become established along contour lines of recessional levels, while the lower zone is invaded in the early spring by seedlings of Russian thistle. Both species are introduced exotics, and tend to lower the quality of the recreational experience.

In 1971, the maximum water level was 3622 feet; in 1972 it was 3620. Therefore, a 2-foot vertical zone of tamarisk was allowed to grow unflooded and by 1973 was 2 years old. Compliance with the court order of February 1973 to hold the water level at 3606, after it had previously been higher, would mean that a 16-foot vertical zone in July and up to a 32-foot zone in January (which could mean a horizontal band hundreds of feet in width) would be allowed to develop into a dense stand of tamarisk and Russian thistle. In most sandy shoreline areas, these exotic plants will develop thick stands.

Most shoreline camping and daytime shoreline use by recreationers, including swimmers, is on sandy beaches. Camping in Russian thistle and tamarisk is a far cry from the natural experience of camping in native vegetation. The rapid growth (4 to 6 feet per year) of tamarisk would soon produce a shrubby entanglement around the shore which would foster increased populations of flies and other insects characteristically rare in native vegetation. The increased density and maturity of the exotics would mean an abundant seed source with increasingly dense yearly invasion of the drawdown zone, which, when reflooded each year, would soon become covered with algal growth and produce undesirable conditions for recreational use and serious deterioration of the value of Glen Canyon National Recreation Area.

Since Judge Ritter's order has been stayed by the Tenth Circuit Court of Appeals, the lake level has risen to elevation 3637 as of July 1, 1973, and is still rising. Enforcement of the elevation 3606 level now by drawdown would result in a 30- to 40-foot vertical zone of dead and decaying vegetation as well as create ideal conditions for the rapid establishment of tamarisk and Russian thistle on the shoreline. Native vegetation will not recover in sandy areas occupied by tamarisk for many decades.

A higher lake level means a longer shoreline, but a longer shoreline does not necessarily mean more, or better, campsites everywhere along the lake. In some areas, a higher level will cause the lake to rise above cliff walls and expose more campsites. In other areas, old terraces will be flooded and new cliff walls will form the shoreline. A higher lake level means, at least for the southern part of the lake, that the water line will be higher up on the Navajo, Kayenta and Wingate Formations, which are all resistant sandstone formations (Figure 6). It is probable that the 3700 level will increase the number of desirable campsites in the

Figure 6

GEOLOGIC COLUMNS

Geologic formations of the Lake Powell region

Source: Modified from "Nomenclature Chart of the Grand Canyon and Adjacent Areas" by C. M. Molenaar, in D. Baars, (Ed.), Geology and Natural History of Grand Canyon Region, Four Corners Geological Society Guidebook, Durango, Colorado, 1969, p. 68.

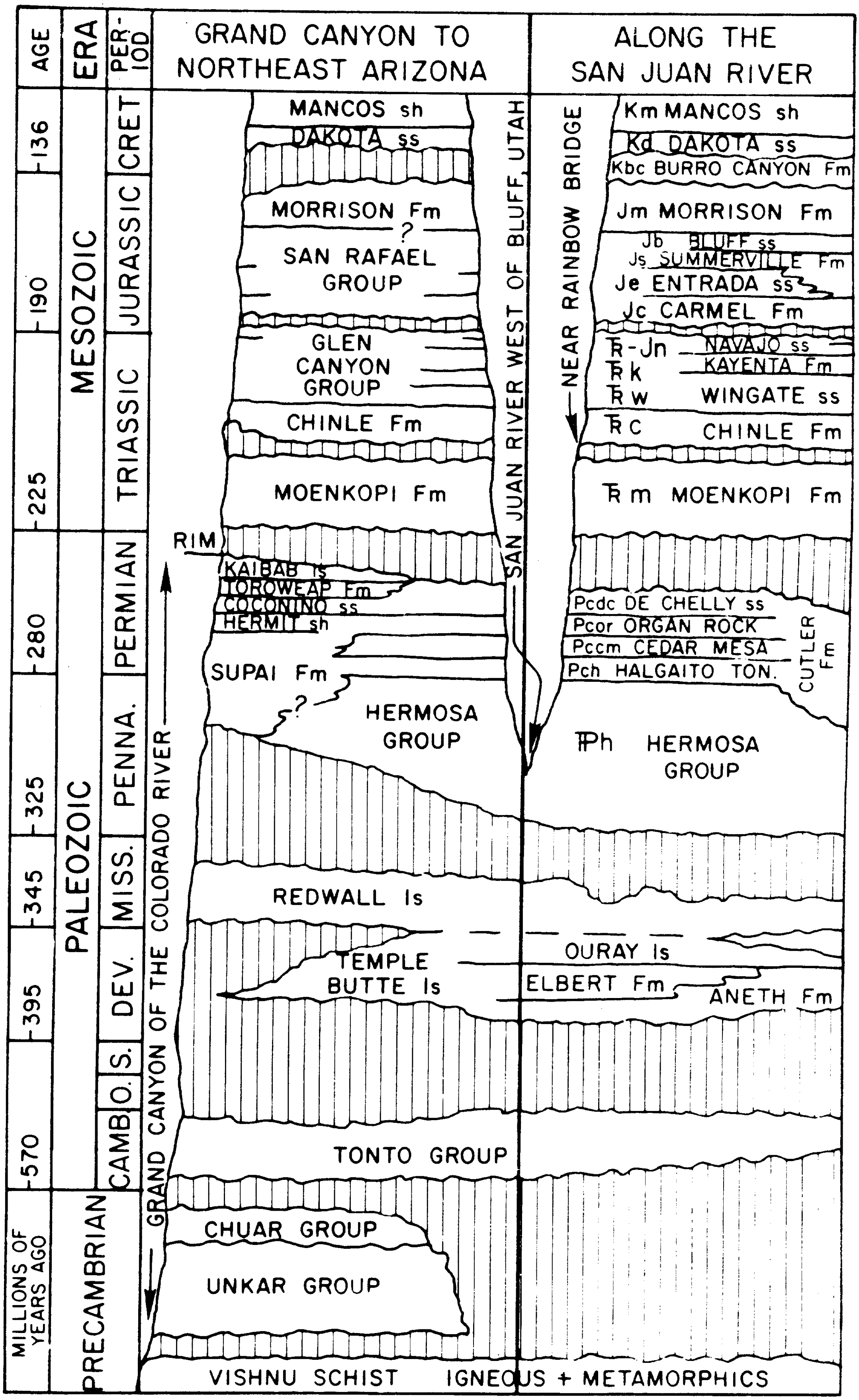


Figure 6:Geologic Columns

northern part of the lake. It is uncertain whether the higher level will increase or decrease the number of desirable campsites in the southern part of the lake.

A channel at Castle Rock is opened at elevation 3625 which allows boaters to proceed directly from Wahweap Marina up the lake towards Rainbow Bridge. At elevation 3600, this channel does not exist and boaters must proceed south toward the dam and then north, adding 11 miles to the trip. Other such channels are available at elevation 3630 and higher levels.

2. Wilderness Preservation

The Project expects that fluctuating lake level will have an adverse effect on wilderness recreation. There will be debris and dead vegetation, the creation of coarse cobbly beaches, and an increase in the invasion of sandy beaches by exotic vegetation which will all tend to disappoint lake visitors seeking to experience desert wilderness. The "bathtub ring" formed by calcium carbonate precipitation will be evident after any drawdown of lake level. Dead vegetation, drowned during periods of higher lake level, will be exposed during drawdowns, and will offend many visitors.

It is anticipated by Project investigators that the effect on wilderness recreation will be mostly adverse if lake level is maintained at maximum capacity. In the lower part of the lake, there would be a visual reduction in the comparative height of canyon walls above the water level, and less dramatic visual canyon experience. The lake will be wider in many areas as rocky shelves are flooded, and the narrowness of some canyons will no longer be as striking. In addition, it will be possible to see the stacks of the Navajo Generating Station near Page from many more areas of Lake Powell if the water level is maintained at the maximum level.

At elevation 3606, the shoreline is on the north side of Rainbow Bridge National Monument at Bridge Creek, and at 3700 the shoreline would be outside the Monument to the south. A delta can be expected to form at the point at which Bridge Creek enters Lake Powell, because the flash floods of the Creek transport sediment and debris. If the lake level is maintained at elevation 3606, this delta will be visible to visitors to the Monument whenever there is a drawdown of the lake. Although the sight of the delta will be aesthetically displeasing, there will be the compensation of the preservation of the natural desert setting at the bridge site. If the lake level were maintained at elevation 3700, the delta would form south of (upstream from) the bridge, and would be out of sight to visitors under the bridge. However, the wilderness experience would be lessened by the appearance of a channel filled with lake water under the bridge. There would be decaying vegetation and mud deposits on the bottom of Bridge Canyon whenever the lake level dropped.

The construction of a coffer dam in Bridge Canyon has been proposed as a way of allowing the lake to rise to elevation 3700 without permitting the lake to enter the National Monument. Although funds have not been appropriated for the construction of such a protective feature, the proposal is revived from time to time. The impact of a coffer dam would depend on the site and particular construction details of the design. Such elements would be revealed in an adequately prepared environmental impact statement. Regardless of the design, however, those who prize wilderness values would likely find the presence of a dam in Bridge Creek more offensive than a delta or mudflat.

The quality of the wilderness experience in the vicinity of Lake Powell will be diminished to the extent that intensity of recreational usage of the lake is increased. It is difficult to determine whether the intensity of recreational use will increase as a direct result of increasing lake level. However, it seems likely that increased biological activity within the lake waters will increase the abundance of fish, and that increased surface area of the lake and variety of campsites would attract more visitors. In this case, the marinas would experience higher commercial demands if the lake were to be operated at its maximum elevation. This would impose heavier demands on campsites, swimming beaches, and shoreline especially in the southern part of the lake. Heavy visitor use would create larger noise levels and gasoline motor emissions, and such factors would degrade the wilderness experience.

3. Regional Air Quality

The quality of experience in both developed and wilderness recreation is contingent upon the quality of air in the recreation area. Air quality is also an important element in the quality of life of the residents of the region. Excellent air quality is basic to the high recreation value of the Lake Powell region, and people are far more demanding of excellent air quality for their recreation than for their everyday working habitat. The motorized equipment essential to developed recreation has a significantly degrading effect on air quality, while the effect of wilderness recreation is limited to emissions from motorized vehicles used for transportation from cities to the wilderness boundaries.

The air quality of the Lake Powell region is excellent, especially in comparison with the air in cities such as Phoenix. For example, the arithmetic annual mean concentration of nitrogen dioxide in Page is 36 micrograms per cubic meter ($\mu g/m^3$) compared to 168 $\mu g/m^3$ in Phoenix and the annual geometric mean mass concentration of aerosol in Page is 18 $\mu g/m^3$ compared to 108-265 $\mu g/m^3$ in Phoenix. The air around Lake Powell loses some of its excellent character near local air pollution sources such as automobiles and motorboats. These sources emit carbon monoxide, hydrocarbons, oxides of nitrogen, aerosols, and noise. The last two parameters of the list are the easiest to measure. The background value of aerosol number concentration is about 1300 particles per cubic centimeter (cm^3), while values near the exhaust of a motorboat or automobile exceed 10^5 per cm^3. The background value of noise is about 23 decibels on the A scale (dbA) while motorboats can produce over 100 dbA.

If the lake level reaches elevation 3700, or drops to 3606, the only direct effect on air quality is the change in water-transfer rate from the lake to the air by evaporation, which is not known at this time. Indirectly, a greatly changed lake level, either up or down, will only affect air quality through a change in the population and density of motorboats and automobiles. For example, at elevation 3700, the greatly increased lake area and shoreline might significantly increase recreation intensity so that marinas would be populated by many more motorboats and automobiles. The opposite might happen at a very low lake level. The air quality at the marinas is strongly dependent on the motorboat and automobile density.

D. Geologic Hazards

There are many rockfalls and landslides in the vicinity of Lake Powell which are characteristic features of the Colorado Plateau. These features are caused by the erosion processes which formed the deep canyons and mesas in a relatively short period in the geological timescale. The action of a rapidly eroding river has been one of the chief agents in forming canyons and mesas by rockfalls and slides, such as are seen in the Glen Canyon area. When a powerful river is replaced by a deep lake, it is not easy to make a general statement predicting whether the erosional process is accelerated or diminished, without detailed geologic examinations. The rate of the process depends very much upon very local geological conditions.

1. Slumping of Unconsolidated Material

There is evidence that landslides are accelerated and promoted where the Chinle Formation underlies sandstone cliffs near the water surface. Chinle Formation is exposed near Castle Butte, near the Rincon, and near Piute Mesa on the San Juan River.

The Lake Powell Research Project crews camp frequently on the edge of the lake in the course of their work. The limnological crews report that there are a great many new slide scars wherever steep slopes of Chinle Formation (see Figure 6 for geologic column) or sand or alluvium were exposed at the waterline. One such slide was actually observed in action on the southeast lakeshore near the Rincon. On the night of June 19, 1973, a number of slides were heard in the vicinity of Trachyte Creek. A particularly severe one occurred at 4 A.M., awakening the crew. The crew observed a series of high waves which followed the sound about 30 seconds later. The waves were large enough to be dangerous to all boats located near the slide, or to smaller boats some distance away from the slide.

Raising the level of Lake Powell is clearly causing intense, geologically rapid, slumping activity in soft or unconsolidated materials. Unstable slopes will tend to collapse at high water, but in time the presently dangerous regions will become less active and again safe for camping. However, a drawdown of the reservoir will again initiate a period of active slumping, because waterlogged sediments will be unsupported above the water line. After many such cycles of reservoir-level rise and fall, the danger should abate. For the immediate future, there is danger to boaters near these areas, and the sound of landslides can be heard in many parts of the canyon.

2. Rockfalls from Cliffs Rising from the Lake

The Project has found some visual evidence that rockfalls, caused by collapsing cliffs of hard sandstone, have been accelerated by the filling of the lake. There are theoretical arguments which indicate that the strength of a cliff face is adversely affected by rising lake level, but it is not possible to verify this prediction without diverting the Project from its present goals of research within budgetary limitations. The Project does not have the manpower or funds to attempt to prove whether or not a lake level of elevation 3700 would increase the rate of rockfalls from high cliffs, over the rate for the lake level at elevation 3606.

3. Rockfalls from Rainbow Bridge

When the possibility of rockfalls at Rainbow Bridge is considered, it is important to note that the geological situation there is very different from that leading to frequent slumps of unconsolidated material often occurring along the lakeshore or the occasional rockfalls from cliffs rising out of the lake.

Rainbow Bridge is composed of Navajo Sandstone resting on a gently sloping base of more resistant Kayenta Sandstone (Figure 7). The inner gorge of Bridge Canyon is cut entirely in Kayenta Sandstone. The Kayenta Sandstone under the bridge consists of hard sandstone layers, which on the west side are massive and coated with desert varnish. The water level of the lake at 3700 feet would be contained within the inner channel of Bridge Creek. The water would be at least 20 feet below the contact between the Navajo Sandstone and the Kayenta Sandstone. In order to conclude that standing water at 3700 feet would accelerate rockfalls from Rainbow Bridge, above the rate of naturally occurring rockfalls, one would have to prove that standing water will incise and undercut the Kayenta Sandstone of the inner gorge under Rainbow Bridge faster than

Figure 7

RAINBOW BRIDGE

Geologic formations of Rainbow Bridge. Depth of water in Bridge Creek canyon is shown for lake elevation 3700.

Source: Outline and dimensions traced from unpublished Bureau of Reclamation diagram

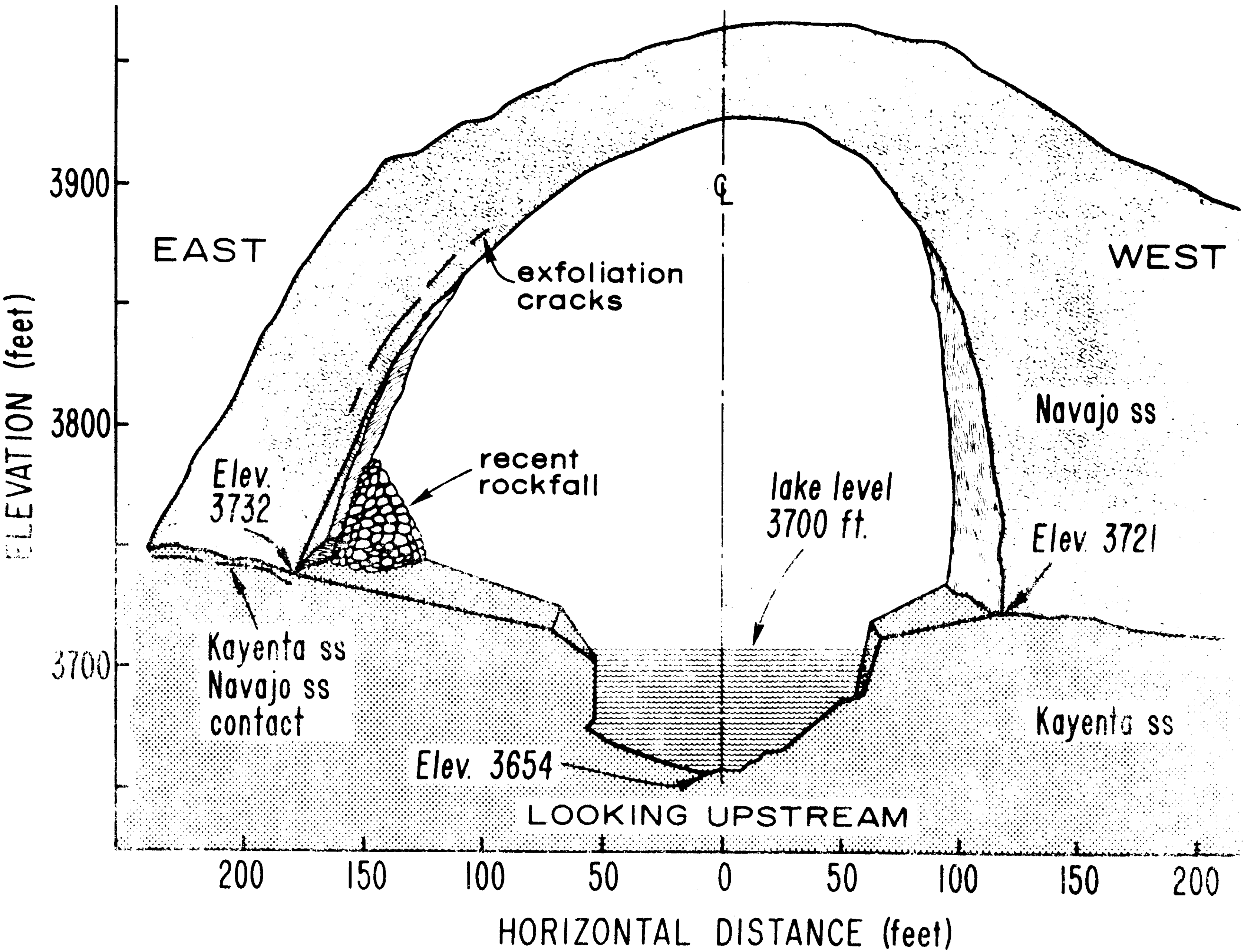


Figure 7: Rainbow Bridge

the flash floods down Bridge Canyon would incise and undercut the same rocks under the bridge.

The Project finds no evidence to contest the conclusion by W. R. Hansen (U.S.G.S. Administrative Report, 1959, "A Geological Examination of Rainbow Bridge National Monument" pp. 18-19) that "there appears to be no valid geologic reason to fear structural damage to Rainbow Bridge as a result of possible repeated incursions and withdrawals of reservoir waters to and from the inner gorge of Bridge Creek beneath the bridge. Rocks within this zone consist entirely of sandstone units of the Kayenta formation, which at the bridge is intermittently saturated by ground water under existing conditions and shows no deleterious effects. Intermittent wetting with reservoir water would only duplicate already existing conditions. The erosive effect of possible wave action in the narrow inner channel would assuredly be negligible and certainly would be less vigorous than the actions of past flash floods, which themselves have not endangered the structural stability of the bridge."

It is important to point out that natural rockfalls are likely from Rainbow Bridge, because the shape of the arch is not yet perfected. This is particularly true on the eastern edge of the arch, where a large pile of rock debris rests against the bridge pillar, and where there are cracks suggesting the shape of the next rockfall. These cracks are caused by a process called exfoliation, which is the natural process by which arches and bridges are formed and perfected in shape in the Glen Canyon region. These natural rockfalls should not endanger the structural stability of the bridge, but they may be expected to occur during the lifetime of the reservoir.

E. Economic Impact

1. Recreational Capacity

The local economic consequences of a 3606 ruling on maximum lake level are determined largely by the effect on the recreational capacity of the lake and by any new construction by the Bureau of Reclamation required to make compliance with the ruling possible.

The recreational capacity of the lake at elevation 3606 might be less than at elevation 3700 because fewer campsites might be available in the northern part of the lake (Section III C 1).

At the 3606 lake level, no channel connects Wahweap and Warm Creek Bays, which necessitates circuitous travel from the southern entrance at Wahweap through the Narrows. Therefore, local congestion in the Narrows area which is already present would be perpetuated. The general congestion of the entire lake is not yet a significant problem, but it may at some point become a deterrent to the use of the lake by tourists and other recreationists, thereby decreasing the influx of recreation dollars into the Powell economy.

2. Marina Locations

At the 3606 maximum level, the silting of the lake at Hite and Piute Farms will compromise existing and future marinas. If the lake is held at elevation 3700, the effect of silting will not hamper marina operations at these sites for some time in the future. The operation of marinas at these two sites would be seriously affected by large seasonal drawdowns of lake level due to the difficulty of operating boats in shallow waters.

Degradation of these sites by silting would have an adverse effect on the economy of the Hite locality and on the possible development by the Navajo Nation of the Piute Farms site. The establishment of a dredging program by the Bureau of Reclamation or the National Park Service would, of course, relieve the problem somewhat, although there is some preliminary indication that recreational use of the Hite area will decline with decreasing attractiveness of the area.

3. Construction of Lower Spillways

If lower spillways were constructed at the dam in order to pass spring runoff at a 3606 maximum level (Section III A), there would be some local economic impact. The Bureau of Reclamation has estimated that about $50,000,000 would be required for construction of a new spillway, since at elevation 3606 the existing spillway system is inoperative (Figure 2). The payroll associated with a $50,000,000 construction activity would be a significant (but temporary) contribution to the Page economy and would have a temporary effect upon the Navajo economy as wage work. The goal of the Lake Powell Research Project is to trace quantitatively this type of dollar influx through the total Lake Powell regional economy.

If lake level were restricted to elevation 3606, power revenues, project payback, and water allocation in the entire Upper Colorado River Basin would be affected. Such extended consequences may have significant economic consequences outside of the Lake Powell region, but very little, if any, on the local economy.

F. Effects Outside the Immediate Lake Powell Region

1. Grand Canyon National Park

If lake level were restricted to elevation 3606, and the present discharge problems remain, there would be an important impact on the ecosystem of the Colorado River in Grand Canyon National Park. High discharges downstream during spring runoff could coincide with high runoffs from the Little Colorado and Paria Rivers.

In this case, the flow characteristics of the river in the Grand Canyon would tend to return to the former natural state with periodic floods separated by seasons with low river flows. The schedule of releases from Glen Canyon Dam would have significant impact on the whitewater recreation in Grand Canyon National Park. Large discharges of clear water will increase scouring of sandy beaches in the canyon. This will reduce carrying capacity and reduce upper level sand bars which are valuable campsites for boat trips.

To the extent that the salinity of the lake is lowered by increased calcium carbonate precipitation for operation at maximum elevation 3700, the salinity of the river water in Grand Canyon will be similarly lowered.

An increased biological productivity near the dam could cause problems to the ecosystem in the Colorado River in the Grand Canyon. More total solid nutrients will be discharged, if the lake level is held at its maximum level. Algal growths already occur downstream which might be further stimulated by increased productivity in the lake near the dam. During particularly warm periods, fish viability may be threatened. This possible event becomes highly probable during periods of low water flow from Glen Canyon Dam. Historically there was little likelihood of downstream effects on fish because the original Colorado River was highly turbid and blocked light penetration. Since the dam was completed, discharge waters lower in silt and light can penetrate deeper into the stream and promote much algal growth.

2. Upper Basin Regional Economic Impact

The Bureau of Reclamation has stated that at the elevation 3606, the "revenues from the sale of power and energy from Glen Canyon Powerplant will be reduced approximately $3,000,000.00 per year, and the loss thereof will impair the financial feasibility of the Storage Project units and Upper Basin participating projects"(Affidavit, Appendix 1). This would delay repayment of participating projects and substantially increase the interest costs. The Lake Powell Research Project has not attempted to evaluate this calculation by the Bureau of Reclamation at this time.

3. Regional Water Allocation (Net Effects)

The net effects from estimates of evaporation and bank storage arising from the two contrasting lake levels of 3606 and 3700 can be evaluated. These effects can be compared with estimates of loss to consumptive use upstream resulting from the two lake levels. The Bureau of Reclamation estimates that 10 maf per decade may be lost for consumptive use if the lake level is kept at or below elevation 3606 (Affidavit, Appendix 1; Section II D this report). As previously mentioned, the Lake Powell Research Project has not checked this calculation.

The Project estimates that the additional evaporation loss if the lake were operated at elevation 3700 instead of 3606 would be about 3.2 maf per decade (Section III A 2). The additional bank storage would be about 2 maf per decade (Section III A 3). Thus total additional losses with a higher lake level would be about 5.2 maf per decade. If the Bureau of Reclamation's estimate of a water loss of 10 maf per decade to the Upper Basin in case of a 3606 level restriction is assumed, and evaporation and bank storage losses are taken into account, it may be estimated that 4.8 maf more water per decade should be available to the Upper Basin if the lake is operated at elevation 3700 instead of 3606.

G. Legal and Political Factors

Stabilizing the level of Lake Powell at approximately elevation 3606 would raise serious questions about the workability of the present "law of the river". i.e., the laws, financial arrangements, and operating criteria that presently govern the management of the river. It must be recognized that other possible future events could converge to provide a wholly independent test of the workability of the "law of the river", separate and apart from the controversy over Rainbow Bridge National Monument. Such possible future developments include (1) worsening water quality under the present water quality standards, (2) enforcement of non-degradation and enhanced water quality standards under the Water Quality Act of 1972, (3) inception of more rigorous water quality standards, (4) initiation of water delivery to the Central Arizona Project, (5) manifestation of Indian water claims, and (6) occurrence of extended drought periods. As noted earlier, Glen Canyon Dam and Lake Powell function to meet a number of legal obligations and policy objectives. If the 3606-foot elevation became a ceiling, power production and carryover storage capacity would be significantly reduced.

Since Glen Canyon Dam is the principal cash register of the Upper Colorado River Basin Fund, reduction in power revenue may weaken the financial condition of the Colorado River Storage Project. This in turn may prejudice further development of the Colorado River Storage Project and create demands for alternate means of financing authorized, but uncompleted, participating projects such as the Central Utah Project.

The resultant reduction in carryover storage capacity would require significant alteration of the operating criteria presently governing the management of the river. Unless major changes were made in existing laws and compacts, it would limit the options of the Secretary of the Interior for balancing uses in the Upper Basin with compact requirements for delivering water to the Lower Basin. For the Upper Basin to meet its obligation to deliver 75 million acre-feet in each 10-year period to the Lower Basin states, it might be necessary for the Upper Basin to curtail its own uses (Section II D).

The prospect of these harmful effects to the Upper Basin might create incentives to seek new institutional arrangements that conceivably could result in improvements in the management of the entire Colorado River. A new basin-wide interstate compact, with or without a regional compact commission possessing broad resource management powers, might evolve. The argument that the boundary between the Upper and Lower Basins should be at Hoover Dam rather than at Lee Ferry might be revived. Such a step in turn might require arrangements to be made for dividing power revenue between the Upper and Lower Basins. Along somewhat different lines, stabilization of the lake level might stimulate increased incentives toward the formation of basin-wide coalitions to seek large-scale interbasin transfers of water, increased investment in and attention to water quality programs, and increased research and development of weather modification technology.

Therefore, the current institutional constraints ought not to be viewed as unchangeable conditions. The legal and political environment in which water decisions on the Colorado River are made, while encrusted with custom, is not static. Given enough inducement, interested parties will seek institutional adjustments.

IN THE UNITED STATES DISTRICT COURT IN AND FOR THE
DISTRICT OF UTAH, CENTRAL DIVISION

FRIENDS OF THE EARTH, et al., Plaintiffs, vs. ELLIS L. ARMSTRONG, Commissioner, Bureau of Reclamation, et al., Defendants.	AFFIDAVIT Civil No. C-116-71

STATE OF UTAH)
) SS.
COUNTY OF SALT LAKE)

DAVID L. CRANDALL, being first duly sworn, states:

1. He is Regional Director of the Upper Colorado Region of the Bureau of Reclamation, United States Department of the Interior, and has responsibility under the supervision of the Commissioner of Reclamation and the Secretary of the Interior for the administration of Lake Powell under the Colorado River Storage Project Act of 1956 (43 U.S.C. 620, et seq., Authorizing Act for Glen Canyon Dam and Lake Powell), and the Colorado River Basin Project Act of 1968 (43 U.S.C. 1552, Requirements for Joint Operation of Lake Mead and Lake Powell). This responsibility includes the release of water from Lake Powell to:

(a) Satisfy the provisions of the Colorado River Compact and the Upper Colorado River Basin Compact as contained in 42 Stat. 171 and 63 Stat. 31, respectively;

(b) Comply with the provisions of the Operating Criteria promulgated pursuant to 43 U.S.C. 1552;

(c) Comply with the provisions of the Colorado River Storage Project Act.

2. He is personally knowledgeable of the physical characteristics regarding Rainbow Bridge National Monument, the Glen Canyon Dam and Powerplant, and with the past operation of Lake Powell. Pertinent facts are as follows:

(a) The lower boundary of Rainbow Bridge National Monument is 3606 feet above mean sea level.

(b) The elevation of the monument directly beneath Rainbow Bridge in Bridge Creek Channel is 3654 feet.

(c) Lake Powell first reached the elevation of 3606 feet and entered the monument on or about May 15, 1971, and was continuously within the monument until September 15, 1972. Lake Powell was also within the monument between October 20, 1972, and January 1, 1973, and has been outside the monument since.

(d) The highest level of Lake Powell was 3622.3 feet attained on or about July 11, 1971.

(e) The highest level of Lake Powell for 1972 was 3619.7 feet, attained June 27, 1972.

(f) The Glen Canyon Dam spillway crest is located at 3648 feet elevation.

(g) At the present elevation of Lake Powell, the hydraulic capacity of the turbines and outlet works at Glen Canyon Dam is approximately 30,000 c.f.s. and 15,000 c.f.s., respectively. No other physical facility is available to release water at or below elevation 3606 feet.

3. Under his direction and prior to February 27, 1973, a plan of operation for Lake Powell, taking into account precipitation, projected stream flows, and statutory responsibilities referred to in paragraph 1, had been prepared by the Bureau of Reclamation. This plan anticipates that:

(a) Lake Powell will reach an elevation of 3606 feet approximately May 1, 1973.

(b) Lake Powell will reach an elevation of 3622 feet about June 1, 1973.

(c) Lake Powell will reach an elevation of 3643 feet about July 10, 1973, which point is the projected high water level for 1973 water year.

(d) Based on the projected snow pack and stream flows, the spring runoff into Lake Powell will be in excess of the 45,000 c.f.s. combined capacity of the turbines and outlet works at Glen Canyon Dam.

4. He personally is knowledgeable of the effect of the waters of Lake Powell within Rainbow Bridge National Monument and has reviewed expert studies on the subject. The nature of the effect on Rainbow Bridge National Monument will be no different by Lake Powell again reaching an elevation of 3622 than it was in 1971 when it reached 3622. The nature of the effect of water of Lake Powell between elevation 3622 and 3643 will be similar to the effect of the original entry of Lake Powell water to elevation 3622. At elevation 3643, the water will be at least 600 feet from Rainbow Bridge.

5. Taking into account the factors in paragraphs 1, 2, and 3, the effect of drastically altering the operation plan for Lake Powell in order not to exceed elevation 3606 feet for only one water year will be as follows:

(a) To create reservoir storage capacity below the 3606-foot elevation in order to pass all anticipated spring runoff through the powerplant, it will be necessary to draw Lake Powell down to approximately 3590 feet elevation.

(b) Approximately 4,000,000 acre-feet of additional water will be released from Lake Powell in 1973 that would otherwise not be released except for the injunction imposed by the court.

(c) The release of an additional 4,000,000 acre-feet of water and the operation of Lake Powell with a maximum elevation of 3606 feet would make it impossible to follow the operating criteria promulgated under the provisions of P.L. 90-537 (43 U.S.C. 1552).

6. Studies of the Bureau of Reclamation show that the continued operation of Lake Powell below 3606 feet elevation will have the following effects:

(a) The Upper Division States of the Colorado River Basin will have their ability to use their Compact apportionment of water pursuant to the Colorado River Compact and the Upper Colorado River Basin Compact reduced by about 1,000,000 acre-feet of water annually because without storage in Lake Powell at the 3700-foot level, upstream water will have to be released to satisfy Lower Basin rights in years of water shortage.

(b) Revenues from the sale of power and energy from Glen Canyon Powerplant will be reduced approximately $3,000,000.00 per year, and the loss thereof will impair the financial feasibility of the Storage Project units and Upper Basin participating projects authorized by the Project Act, as amended.

(c) The Operating Criteria set out in P.L. 90-537 (43 U.S.C. 1552) and the Congressional directives in the Colorado River Storage Project Act cannot be met.

David L. Crandall
David L. Crandall

Subscribed and sworn before me this 13th day of March, A.D., 1973.

Thomas O. Parker
Notary Public
Residing at Salt Lake City
County of Salt Lake
State of Utah

(SEAL)

My Commission Expires:
August 19, 1976.

Appendix 2. Disciplines and Senior Personnel in the Project

NATURAL SCIENCES

<u>Atmospheric Physics</u>

Eric G. Walther, Northern Arizona Society of Science and Art, Inc. (Museum of Northern Arizona)

Michael D. Williams, Los Alamos, New Mexico (John Muir Institute)

<u>Biology</u>

David E. Kidd, University of New Mexico

Loren D. Potter, University of New Mexico

<u>Environmental Impact Analysis</u>

Max Linn, (John Muir Institute)

Luna B. Leopold, University of California, Berkeley (John Muir Institute)

Robert W. Twiss, University of California, Berkeley (John Muir Institute)

Helen Ingram, University of Arizona (John Muir Institute)

<u>Geology and Geophysics</u>

Charles L. Drake, Dartmouth College

Orson L. Anderson, University of California, Los Angeles

John W. Handin, Texas A & M University

Priscilla C. Perkins, University of California, Davis

<u>Hydrology and Dendrohydrology</u>

Gordon D. Jacoby, Jr., University of California, Los Angeles

Charles W. Stockton, University of Arizona

<u>Physical Limnology and Water Geochemistry</u>

Noye M. Johnson, Dartmouth College

Robert C. Reynolds, Dartmouth College

SOCIAL SCIENCES

<u>Anthropology</u>

Jerrold E. Levy, University of Arizona

Lynn A. Robbins, Western Washington State College

<u>Economics</u>

Shaul Ben-David, University of New Mexico (John Muir Institute)

F. Lee Brown, University of New Mexico (John Muir Institute)

<u>Epidemiology</u>

Stephen J. Kunitz, University of Rochester

<u>Law</u>

Monroe E. Price, University of California, Los Angeles

Gary D. Weatherford, Ferris, Weatherford and Brennan, Inc. (law firm) San Diego, California

<u>Political Science</u>

Dean E. Mann, University of California, Santa Barbara

Appendix 3. A Summary of the Subprojects

No.	Title	Institution*	Principal Investigators
1.	Systems Analysis	JMI	Ben-David & Brown
	To develop a model expressing relationships of various subprojects--as it may be useful to regional development and resource management policy-making, and to develop a mechanism of responding to public issues and other problems as action variables.		
2.	Biological Limnology	UNM	Kidd
	To develop indices of eutrophication, measures of primary productivity, and to understand impact of man on reservoir aquatic ecology.		
3.	Shoreline Ecology	UNM	Potter
	To examine the ecological changes related to rising water level in terms of nutrient and organic matter enrichment as a base for establishing indices for carrying capacity and public use.		
4.	Heavy Metals	UNM	Potter & Kidd
	To examine the concentrations of metallic cations in the Lake Powell ecosystem as they occur laterally across the basin and vertically through trophic food chains, as one aspect of man's impact upon quality of the environment.		
5.	Streamflow Trends	UCLA	Jacoby & Stockton
	To utilize dendrochronologic techniques to develop past run-off characteristics in order to better understand space and time variations in runoff and available surface water.		
6.	Lake Evaporation	UCLA	Jacoby
	To develop data stations to record information to calculate evaporation losses via mass-transfer and energy-budget methods in cooperation with on-going Bureau of Reclamation programs to determine net evaporative losses.		
7.	Bank Storage	UCLA	Anderson & Jacoby
	To more accurately determine the quantity and location of the infiltration of water into bank storage and to assess its availability to potential users.		
8.	Physical Limnology	Dartmouth	Johnson
	To examine factors related to meromixis in Lake Powell, to provide baseline data on circulation and currents within the Lake as it approaches full volume.		

9.	Lake Geochemistry	Dartmouth	Reynolds

To examine time-dependent distribution of chemical elements in the Lake; to quantify ions added to the Lake by solution and/or chemical precipitation.

10.	Sedimentation	Dartmouth	Drake

To determine sedimentation rate, distribution, and origin and methods of deposition as they may affect life of the reservoir and its usefulness.

11.	Background Air Quality	NASSA (MNA)	Walther & Williams

To analyze the state of the atmosphere in Lake Powell region without the influence of man; to identify and define air quality parameters not presently being measured to facilitate measurements of change.

12.	Impact Analysis	JMI	Linn, Twiss, Leopold, & Ingram

To examine various environmental impact statements to develop a framework for utilization in policy definition and decision-making regarding utilization of the Upper Colorado River Basin.

13.	Economics	JMI	Brown & Ben-David

To investigate specific functional dependencies of economic variables upon activities related to recreation, power, and irrigation in the Lake Powell area.

14.	Epidemiology	U. Rochester	Kunitz

To develop baseline data regarding relations between diseases and environmental factors to allow for making predictions regarding impact of Lake Powell on resident populations.

15.	Anthropology	U. Arizona W. Wash. St.	Levy Robbins

To study the social and economic impact of the Lake Powell region and its attendant power, mining, and tourism on the Navajo and his decision-making related to legal and political issues.

16.	Law and Political Science	UCLA	Price
		UCLA	Weatherford
		UCSB	Mann
		UCD	Perkins

To examine historically the legal decisions and institutions related to upper basin water development and to determine the extent to which environmental protection and native interests have been recognized or denied, and the extent to which scientific research has been used in water management decisions.

17.	Coordinators Office, Natural Sciences	UCLA	Anderson
		UCD	Perkins

To coordinate research in natural sciences. To represent the Project to NSF. To plan and adminster meetings. To publish reports and bulletins. To coordinate between governmental bureaus, state organizations, and environment interest groups, and the Project's natural science research.

18.	Coordinator Office, Social Sciences	U. Arizona	Levy

To coordinate research in social sciences. To coordinate between governmental bureaus, Indian tribes, state organizations and environmental interest groups and the Project's social science research.

* UNM = University of New Mexico; UCLA = University of California, Los Angeles; UCD = University of California, Davis; UCSB = University of California, Santa Barbara; NASSA = Northern Arizona Society for Science and Art, Inc.; JMI = John Muir Institute; MNA = Museum of Northern Arizona.